TRIP REPORT

Travel by D.A. Powers to Attend the High-Temperature Gas-Cooled Reactor Safety and Research Issues Workshop Rockville, Md., October 10-12, 2001

D.A. Powers

Advisory Committee on Reactor Safeguards

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DISCLAIMER: The views expressed in this report are solely those of the author and do not represent any position adopted by the Advisory Committee on Reactor Safeguards

INTRODUCTION

This trip report describes the proceedings of a workshop held in Rockville, Maryland, on October 10-12, 2001 to discuss research needed to support the certification of the Pebble Bed Modular Reactor (PBMR) design. The PBMR design was discussed at some length at a recent meeting of the Advisory Committee on Reactor Safeguards' Subcommittee on Advanced Reactors. Consequently, it is assumed here that readers have a general familiarity with the overall design concept. The reactor is gas cooled and graphite moderated. It uses coated particle fuel. That is, uranium dioxide fuel coated with layers of porous graphite, silicon carbide and dense graphite. These particles are distributed in balls of graphite. The balls of fuel are arrayed in an annulus about a column of graphite balls that do not contain fuel and act as a reflector. The balls of fuel cycle through the core region over a period varying between 60 and 100 days. Control and shutdown capabilities of the reactor are located in the graphite reflector that surrounds the core.

The design of the PBMR is sufficiently different from currently licensed reactor designs that it is not evident that the processes used to certify the designs of the Evolutionary Light Water Reactors and the Passive Light Water Reactor can be adapted to certify that the design poses no significant threat to the health and safety of the public. New considerations will come into play in the regulatory examination of the PBMR. Any research needed to develop and support these new licensing considerations needs to be undertaken now to have timely results. The purpose of the meeting was to gather together those who have had experience with gas cooled and graphite moderated reactors to identify important areas of research that should be undertaken by the Nuclear Regulatory Commission.

An agenda for the meeting is shown in Table 1. The specific meeting objectives were to:

- define the dominant accident scenarios for high temperature gas-cooled reactors
- define criteria for ranking the importances of the accident scenarios
- identify primary phenomena, processes and safety issues for each scenario
- discuss research needs for high priority safety issues

The meeting attracted sufficient interest that both the Office Director of Nuclear Regulatory Research at NRC, Ashok Thadani, and the Chairman of the Nuclear Regulatory Commission, Richard Meserve, gave opening addresses. General presentations were made following these opening remarks, and the discussions of the attendees followed. Attendees at the meeting included experts from Germany (Dr. Gerd Brinkmann), Japan (Dr. Toshiyuki Tanaka), Russia (Peter Fomichenko), South Africa (Guy Clapisson), Great Britain (William Ascroft-Hutton and Lyn Summers), China (Professor Xu Yuanhui), International Atomic Energy Agency (Marco Gasparini), Dr. Thomas S. Kress of the Advisory Committee on Reactor Safeguards as well as representatives of the Department of Energy and the National Laboratories.

The most significant observations and conclusions reached by the author of this trip report as a result of his participation in the meeting are presented summarily in the next section of this report. More detailed descriptions of the proceedings of the meeting are provided in the third section of this report. It is, of course, emphasized that views expressed here are solely those of the author of the report and do not indicate any position adopted by the Advisory Committee on Reactor Safeguards.

Table 1. **Agenda for the High-Temperature Gas-Cooled Reactor Safety and Research Issues Workshop**

Wednesday, October 10, 2001

8:30 am	Welcoming Address by NRC Research Director
8:40 am	Opening remarks by the NRC Chairman
9:00 am	Overview of NRC Advanced Reactor Research
9:10 am	Scope, Goals and Expected Outcome for Workshop
9:35 am	General Description of the Pebble Bed Modular Reactor
10:00 am	NRC's Pre-application Activities for the Pebble Bed Modular Reactor
11:00 am	Status of Licensing Review in South Africa for the Pebble Bed Reactor
11:45 am	Safety and Research Issues Identified in MIT Pebble Bed Reactor Project
1:15 pm	Overview of the Workshop Structure and Approach
1:45 pm	Identification of High Temperature Gas Reactor Event Scenarios
3:30 pm	Discussion of Steady State Operational Issues

Thursday, October 11, 2001

8:30 am	Discussion of Loss of Forced Cooling Scenarios
1:15 pm	Discussion of Air Ingress and Water Ingress Scenarios
3:30 pm	Discussion of Seismic Scenarios

Friday, October 12, 2001

8:30 am	Reactivity Event Scenarios
10:30 am	Summary of Workshop
12:15 pm	Adjourn

SIGNIFICANT OBSERVATIONS AND CONCLUSIONS

Significant observations and conclusions reached by the author of this trip report as a result of participating in the meeting are listed below:

- **As currently designed, the Pebble Bed Modular Reactor does not conform with the defense in depth regulatory philosophy of the Nuclear Regulatory Commission and could not be certified.**

There is a firm defense in depth strategy embedded in the design of power reactors currently operating in the USA. In contrast to what might be argued by those of the rationalist persuasion, this defense in depth has nothing to do with compensating for uncertainties of aleatory or epistemic natures. It has to do with the certainty that it is simply impossible to anticipate all the misadventures and combinations of disruptive events that can afflict creation of man. Designers and operators of the current generation of reactors are certain that no matter what happens, their first objective is to get water on the reactor fuel. They want to cool the core and the way to do this is with water. Even if water cannot be supplied in the quantity or the way that leads to prompt quench of the fuel, the water will attenuate the release of radionuclides that pose the hazard to the public. In the long term, water will cool the fuel eventually if it can continue to be supplied. The operators and designers seek this safe haven of a water-cooled core whether the disruptive event has been initiated by stochastic equipment failures that PRAs can calculate, by human errors of omission or commission that PRAs may someday be able to calculate, or by sabotage or terrorist act which analysts despair of ever being able to calculate.

There is no similar safe haven for the Pebble Bed Modular Reactor. What recourse does the reactor operator have once he has lost high pressure helium coolant? He certainly does not want to replace the helium flow with a flow of air which is the only other abundantly and readily available gaseous coolant. Air will react exothermically with the core and exacerbate the disruption. It will augment rather than attenuate the release of radionuclides. The operator cannot turn to water to cool the core because water will cause the under moderated core to go critical which is certainly not an acceptable turn of events. In the end, some argue that conduction of heat will mitigate the accident, but conduction into soil and concrete is not likely to prevent high temperatures developing in a disrupted core and the extensive release of fission products.

There may be solutions to the lack of defense in depth inherent in the current design for the Pebble Bed Modular Reactor. Currently proponents of the design feel the solution is to make it ever less likely that loss of coolant events will occur. This focus on prevention of events flaunts defense in depth and everything that has been learned in the past two decades of quantitative risk analysis. A defense in depth safety philosophy requires that there be some balance between prevention and mitigation. Both prevention and mitigation must be available to achieve the very low levels of risk found palatable to the public for nuclear power.

An approach to the failings of the current design for the Pebble Bed Modular Reactor that is more consistent with the defense-in-depth safety philosophy would be to design a way to disperse the core over a broad area such that it could be cooled with water in the event of loss of cooling capabilities. Apparently, the Russians have considered a 'core dump' capability in their test reactor.

- **The Pebble Bed Modular Reactor core may be susceptible to neutronic instabilities.**

The current design for the Pebble Bed Modular Reactor involves a long, low diameter annulus of active fuel. Fuel balls move through this annulus. The fuel density within the annulus varies both spatially and temporally as moving balls achieve various levels of imperfect packing density. The fuel balls do not have centers of gravity coincident with their geometric centers and may, in fact, have multiple, metastable equilibrium positions. Their motions are, then, chaotic and inherently not predictable locally. Wear and damage to the fuel balls during normal operations will make ball motions all the more unpredictable and the temporal and spatial variations in core power greater. Furthermore, the core is "loosely coupled" neutronically. This is all a prescription for core instability akin to the kinds of instability encountered in boiling water reactors. The potential instability is made worse because control rods are not distributed within the local regions of the core, but are arrayed outside the core.

- **The shutdown system for the current Pebble Bed Modular Reactor is not adequate**.

The Pebble Bed Modular Reactor has two shutdown systems. But, the temperature coefficient of reactivity is very high. With just one shutdown system deployed, the core can become critical as it cools. Both systems are required to prevent recriticality. The two systems are, then, not redundant. South African regulatory authorities are mandating that this aspect of the design be changed. This feature of the design does make clear how complicated neutronic analyses for regulatory purposes will have to be for the Pebble Bed Modular Reactor.

- **The Pebble Bed Modular Reactor is not proliferation resistant**.

The Pebble Bed Modular Reactor uses online refueling. Fuel ball, each of which contains about 9 grams of heavy metal, circulate through the core over a cycle that might be as long as 100 days or as short as 60 days. As the balls emerge from the core, they are remotely inspected and either recirculated into the core or sent to the spent fuel pool. It is not beyond imagination that balls loaded with depleted uranium could be included in the fuel loading. Exposure of these balls of depleted uranium to the neutron flux for about 90 days is usually considered an optimum for the yield of ^{239}Pu without overly high contamination by non-weapons grade isotopes of plutonium. It appears to me, then, that the Pebble Bed Modular Reactor is tailor made for the facile production of weapons grade plutonium. Some argue with this interpretation by citing the number of fuel balls it would take to produce useful amounts of weapons grade plutonium. I don't really take this argument too seriously. Weapons grade plutonium production has always been a low-yield process. Others argue against proliferation by examining the plutonium isotope production in the enriched (8% ^{235}U) fuel particles which would never be considered a practical way to make plutonium. They need to look at how one would cycle depleted uranium balls or targets through the core.

○ **High temperature radiation damage to graphite**

Though most seem to be aware of the Wigner energy that can be stored in irradiated graphite at low temperatures, there does not seem to be a keen awareness of the radiation damage that can occur in graphite at high temperatures. These high temperature radiation damage processes involve higher energies than the Wigner effect. The energy stored in graphite by these radiation damage processes will be released if the graphite is heated to sufficiently high temperatures in an accident or if the graphite is chemically reacted. It is not apparent that accident analyses have considered this source of stored energy in predicting the response of the reactor.

○ **Containment versus Confinement**

The Pebble Bed Modular Reactor design proposes to use a confinement rather than a containment. The debate over these two approaches is probably not worthwhile. Containments are used for all the commercial power reactors in this country. But, it should be remembered that the nuclear material production reactors operated by the Department of Energy used confinements. Each concept has its advantages and disadvantages. The real issue is whether the proposed confinement concept provides the level of accident mitigation consistent with the defense in depth safety philosophy.

PROCEEDINGS OF THE MEETING

An attempt is made in the subsections below to provide summary accounts of the proceedings of the workshop. As is the nature of workshops, the well crafted agenda suffered some ad hoc alterations as discussions progressed and the disciplined progression envisaged in the agenda broke down some.

- **Goals, Scope, Approach and Expected Outcomes**

T. King provided a description of the goals of the workshop:

- provide a forum for discussion of high temperature gas-cooled reactor safety and research issues
- provide information useful to NRC in developing an integrated research program for high temperature gas-cooled reactors
- facilitate international cooperation on high temperature gas-cooled reactor research

The technologies of interest included pebble bed modular reactors, prismatic design gas reactors, Brayton cycles, and coated fuel particles. Forecasted schedules for gas reactors were based on fuel loading for a pebble bed reactor in 2007 and fuel loading of a prismatic gas reactor in 2008. King indicated that the workshop discussion would be on:

- important accident scenarios that could lead to release of radioactive material
- important accident phenomena
- important safety needs
- research needs
- priorities

He recognized that it would not be possible to delve into much detail about scenarios, but that it was important to understand the issues and research needs. A transcript of the discussions was kept. Along with the transcript the important outcomes of the workshop were to be:

- list of important phenomena and safety issues
- list of research needs to address the safety issues
- list of research programs planned or underway
- relative priorities

These outputs would be used by NRC as input to the development of a research plan for gas reactors and to identify opportunities for cooperative research.

At the conclusion of King's talk, Ralph Meyer gave an abbreviated discussion of the Phenomena Identification and Ranking Table (PIRT) process that had been used with great success by NRC in dealing with the issues of high burnup fuel. Meyer indicated that the process was time consuming and expensive, but that it yielded insightful results that could be used to design research programs. The Workshop amounted to the first step in the PIRT process. Meyer did not say that it is usually found in these identification and ranking processes that the first step is often the lowest productivity step.

- **Design, Operation and Safety Aspects of the Pebble Bed Modular Reactor**

S. Rubin and D. Carlson of NRC gave a synoptic account of the design of the Pebble Bed Modular Reactor. Most members will be familiar with this design. The only parts of the design that the author of this report found remarkable were:

- extensive use of water cooling in the design
- the idea of having fuel balls in an annulus around a column of reflector balls

The pressure vessel is conventional SA532 class B pressure vessel steel so the vessel has to be kept in the temperature range of 280 to 300° C. The exit temperature of gas from the core is 900°C and the inlet temperature is 500°C. Consequently the design involves cooled helium flowing between the core and the pressure vessel. Water cooling of the reactor cavity is also used to keep both steel and concrete within acceptable temperature ranges.

Up to 10 reactor modules will be located at a site. It is anticipated that on a shift there will be 3 operators (Yes, I believe this is for all 10 modules!) and a total staff of 80. The limited staff and the reliance on computer systems raise substantial issues of human reliability especially with respect to diversion of attention and errors of commission.

Safety objectives and characteristics of the pebble bed reactor are:

- manufacture fuel with very low particle defect rate matching German quality standards
- qualify PBMR fuel with performance equivalent to German pebble fuel
- ensure that core operating and design basis accident conditions do not exceed fuel qualification envelope which is 80 GWd/t, 1250°C and maximum operating temperature of 1600°C
- high temperature performance with ceramic fuel materials
- control graphite chemical attack by oxidation from air and moisture
- provide diverse active scram systems
- provide passive reactor shutdown mechanisms including low excess reactivity and large, negative temperature coefficient of reactivity
- operate at low core power density and large core thermal heat capacity
- utilize a coolant that does not change phase
- provide passive decay heat removal processes that does not rely on helium coolant
- heat exchange with water is done at locations below the bottom of the core with helium pressures above the water pressure
- use a confinement building to limit the available air volume for graphite oxidation
- limit need for operator actions in the event of an accident

The packing density of the fuel balls in the core is not really known. It is likely to vary with time and location in the core. They anticipate a 61% packing density versus the theoretical of 74% for uniformly sized spheres. I am not sure why they expect such a high density. Usually random packing of uniform spheres is less. It is clear that as the balls settle down through the core the packing density will vary. It might well be higher near the bottom than at the top near the point of injection of the recycled balls. There may be a severe control problem because of the varying packing density of the fuel balls.

Prediction of the motions of the fuel balls must be impossible (not just difficult, impossible). The fuel balls are loaded with coated particle fuel pellets. The loading is not uniform so it is quite unlikely that the center of gravity of a fuel ball will coincide with the geometrical center or even that the displacement of the center of gravity from the geometrical center will be consistent from ball to ball. It may well be that a ball will have multiple, nearly equivalent, metastable points of equilibrium. This will mean that the motions of the balls are chaotic and hence not predictable. I do not know whether the nonuniformity of ball motions and packing will be on sufficiently small scale that average treatments are adequate.

There was some discussion of fission product release from fuel. A tenet of faith is developing that at temperatures below about 1600 °C there is no release of fission products from coated particle fuel. This is, of course, not correct. Fission product release from fuel is a function of both time and temperature. It was also noted that all of the test data for fuel had been obtained by heating fuel to a temperature and holding it at that temperature. There had been no tests in which the fuel was put through realistic thermal transients that could thermally shock the silicon carbide cladding on the particle.

- **GT-MHR General Description**

Don Carlson of the NRC provided a description of the General Atomics GT-MHR reactor. This reactor was not the focus of much of the discussion at the workshop, so the description of this reactor is not considered further here. Many of the same safety and research issues identified for the Pebble Bed Modular Reactor will apply as well to the GT-MHR.

- **South African Regulatory Activities with respect to the Pebble Bed Reactor**

G. A. Clapisson provided a review of some of the activities of the South African regulatory authorities with respect to the Pebble Bed Modular Reactor. They do require that each plant have a probabilistic risk assessment. It appears, however, that this risk assessment does not include accidents initiated by fire. They require any licensee to have an adequate emergency plan.

The South Africans have conducted some studies of anticipated transients without scram. They have found that with increasing burnup that the fuel has a decreasing ability to sustain sudden energy inputs. They have made a regulatory decision that existing limits on fuel burnup are adequate protection against this vulnerability of coated particle fuel.

The South African regulatory authority is suspicious of the column of reflector balls in the center of the core. They are studying it further.

They have found that the shutdown system is not diverse. They find that the reactor can become critical as it cools if only one system is deployed. both systems are required to keep the reactor shutdown. They are asking the designers to re-examine the shutdown system. It is an open question whether a shutdown system outside the core will ever be acceptable.

- **Pebble Bed Research at MIT**

A. Kadak described the research his group at the Massachusetts Institute of Technology (MIT) is doing for the Pebble Bed Modular Reactor. They are developing a Monte Carlo model of the core that includes chemical modeling of the fuel. They are particularly concerned about debonding of the graphite from the fuel kernels. They do see variability of the power density in the core with time. The calculate tangential stresses sufficient to cause failure of the pyrolytic carbon and silicon carbide layers in the coated particle fuel. They are now thinking of looking at zirconium carbide as a replacement for silicon carbide in the fuel particle construction. They have identified an attack on the fuel coating by fission-produced palladium. They are looking at core physics with the MNCP and VSOP codes calibrated by comparison to critical experiments done at the

Paul Scherrer Institut in Switzerland, the HTR-10 reactor in China and the ASTRA critical experiments done in Russia.

○ Design basis accident conditions

T. Tanaka described some calculations of the source term during design basis accidents at gas reactors. For these design basis accidents where fuel is kept below 1500 °C, the predominant sources of radioactive cesium and iodine may come from materials plated on the surfaces in the reactor rather than from the fuel. Dr. Tanaka indicated inventories of 110 teraBecquerel of ^{131}I and 130 teraBecquerel of ^{137}Cs. He showed lift-off fractions of the inventories that ranged up to about 40% for iodine and about 15% for cesium.

○ Discussions

Discussions arrived at the following list of topics for consideration:

- air ingress accidents
- water ingress accidents
- accident performance of the coated particle (Triso) fuel
- verification of codes
  - system level codes
  - neutronic codes
  - margins and uncertainty quantification

- reactivity accidents
- Brayton cycle with inline turbines
- release of fission products from overheated fuel
- high temperature materials especially graphite
- central pebble bed reflector column
- fuel temperature limits and margins

A participant from Oak Ridge made the argument that little of the available data on radiation effects on graphite would be useful. The irradiation response of graphite is very dependent on the details of manufacture and no one has been making nuclear grade graphite for a long time. What would be produced now would be different than what had been studied in the past. I am not sure I agree with this position entirely. Some effects are subtle and do depend on microstructural and impurity details. From a regulatory perspective more dramatic effects are usually of more interest and these are not so dependent on the precise details of manufacture. What was surprising is that there seemed to be a poor awareness of the temperature dependence of radiation damage to graphite. Most seemed to be aware of the low temperature radiation damage that afflicted the Windscale reactor (the so-called Wigner energy effect), but did not seem to be aware that there were modes of damage that would not be annealed at the operating temperatures of the Pebble Bed Modular Reactor. Like the Wigner energy, these high temperature radiation damage effects will store energy in the graphite. This energy will be released when the graphite is chemically reacted or heated to a sufficiently high temperature. It is not evident that the stored energy has been taken into account in the analyses of plant responses to accidents.

○ Containment versus confinement

The Pebble Bed Modular Reactor is to have a confinement rather than a containment. The various gas research reactors also have used confinements. There was an attempt at the meeting to understand why the research reactors had elected to use confinements rather than containments. It appeared that containments had never been seriously considered for the research reactors because of cost and the impact on operability. Confinements were used for the Savannah River reactors and the N reactor which were operated by the Department of Energy for the production of nuclear materials. Confinements are not as susceptible to catastrophic failure and large, "puff" releases of radioactivity as containments. With adequate filtration capabilities, confinements could provide high levels of safety and source term reduction. They do need to be robustly designed like the containments for the Savannah River reactors to avoid failures by missiles produced by some of the more energetic severe accident processes.

○ Other discussions

As the workshop progressed, it became more difficult to keep track of the flow of discussions. Points of interest that arose in the discussions included:

- there are those that think air ingress accidents are not credible
- there are those that think water ingress accidents are not credible despite the heavy use of water cooling in the Pebble Bed Modular Reactor design
- there are those that continue to think nuclear grade graphite will not burn in air.

The later of these points is absolutely remarkable after the Chernobyl accident (Not to mention Windscale!). The issue may well be more semantics than anything else. Graphite does not vaporize and combust the way many familiar fuels do when they burn in air. Still graphite does very much react with air and this reaction can be catalyzed by transition metals and by cesium hydroxide.

○ **Conclusions**

The meeting concluded by preparing tables of research needs. The more salient points of these tables are reproduced below:

Table 2: Research Needs Associated with Air Ingress Accidents

- kinetics of high temperature oxidation of graphite
- applicability and adequacy of codes
- termination of sequence
- fuel and fission product release
  - in helium
  - following air ingress

- applicability of current data base to recent graphite forms
- determination of event initiators
  - thermally induced fatigue
  - vibration induced fatigue
  - seismic events initiating accidents
  - embrittlement
  - corrosion
  - failure of turbo-machinery within the primary circuit
- testing recent graphite forms
- probabilistic risk assessment
- fuel particle testing

Table 3: Research Needs with Respect to High Temperature Materials

- carbon-steel pressure boundary and applicability of ASME code case 499
- applicability of ASME code cases for gas reactor applications
- procedure for evaluating fatigue and creep effects of impurities, ratcheting, erosion of graphite
- use of thermal expansion joints, slip joints, bellows etc.
- thermal aging
- inservice inspection approach for reactors that have little downtime
- carbon composite materials for control rods
- failure modes of rotating machinery
- particulate content of circulating gas
- core barrel materials
- accident conditions a requirements with respect to piping and vessels

Table 4: Research Needs with Respect to Graphite

- what graphites will actually be used
- graphite growth, differential stresses with flux and temperature gradients
- graphite corrosion
- keyway stresses and stress concentrations
- graphite dust generation and deposition
- graphite distortion and effects on scram system
- graphitization of pebble matrix
- radiation induced creep at high doses
- methods for monitoring incore graphite
- graphite dust effects on source term during operations and accidents
- inservice inspection of graphite
- impurities to and from the coolant

Table 5: Research Needs with Respect to Fuel Performance

- fuel failure fractions
- applicability of current Triso fuel data base
- sufficiency of steady-state fuel evaluations of fuel performance versus realistic transient tests
- rate limiting steps in the fission product release processes
- fuel qualification approach - process evaluation or product evaluation?

Table 6: Research Needs with Respect to Loss of Forced Circulation Accidents

- understanding of heat rejection mechanisms when there are equipment failures
- concrete response to elevated temperatures
- use of test data from non-annular cores to validate codes for the annular core
- graphite thermal conductivity as a function of temperature
- core hot spots
- reactivity changes in core induced by changes in packing fraction
- effects of pressure waves following turbine trip

Table 7: Research Needs with Respect to Seismic Events

- structural response of graphite to seismic event
- neutronic response of core to changes in packing density induced by vibration
- graphite toughness variations with time and duty
- response of shutdown rods to seismic vibrations
- shutdown system diversity